II.5 Solid State Energy Conversion Alliance (SECA) Solid Oxide Fuel Cell Program

Nguyen Minh (Primary Contact), Ray Andrews, Tony Campbell
GE Hybrid Power Generation Systems
19310 Pacific Gateway Drive
Torrance, CA 90502-1031
Phone: (310) 538-7250; Fax: (310) 538-7250; E-mail: nguyen.minh@ps.ge.com

DOE Project Manager: Travis Shultz
Phone: (304) 285-1370; E-mail: Travis.Shultz@netl.doe.gov

Objectives

- Develop a fuel-flexible and modular system (3 to 10 kW) that can serve as the basis for configuring and creating low-cost, highly efficient, and environmentally benign power plants tailored to specific markets.
- Demonstrate a prototype system of the baseline design with desired cost projections and required operating characteristics (Phase I); assemble and test a packaged system for a selected specified application (Phase II); field test a packaged system for extended periods (Phase III).

Approach

<u>Phase I</u>

- Establish a baseline system concept and analyze its performance characteristics.
- Perform a cost study to estimate system costs.
- Develop a robust, reliable, high-performance solid oxide fuel cell (SOFC) stack technology amenable to low-cost manufacturing.
- Develop a fuel processor as a pre-reformer for processing a variety of fuels.
- Evaluate system thermal management to establish a suitable recuperation scheme for the system.
- Develop and implement a flexible control structure incorporating required sensors.
- Identify a flexible low-cost power management subsystem.
- Evaluate component integration.
- Assemble and test a prototype system to demonstrate performance meeting the program requirements.

Accomplishments

<u>System Design and Analysis</u>

- A conceptual 5-kW system has been designed, and its performance and operating characteristics have been analyzed. When fully developed, the estimated system efficiency on natural gas is about 40%. A failure modes and effects criticality analysis for the system has been completed.
- Preliminary prototype system design, including analysis of initial baseline design, was completed.

<u>Cost Estimate</u>

- Projected cost estimates were updated and cost report submitted.

Stack Technology Development

- Several module and stack tests of the SECA stack design were conducted. A single-cell module, running at 88% fuel utilization in simulated autothermal reforming (ATR) reformate containing 7% methane, achieved a power density of 0.276 W/cm^2 at the SECA design current of 0.428 A/cm^2. This compares favorably with the target of 0.300 W/cm^2 under the same operating conditions.
- Extraordinarily high fuel utilization (95%) has been demonstrated with the half sealed stack design.
- A 10-cell stack of the SECA stack design was tested and achieved a peak power of 503 W.
- A design iteration on the stack was performed. The new design retains the positive features of the previous design and incorporates new features to improve thermal cycling and sealing.
- The fuel cell cathode was improved. Initial performance improvements of 20% were observed, and the new cathode retains its performance at approximately 1/3 the thickness of the standard cathode.

Fuel Processing

- The ATR pre-reformer has been designed. The pre-reformer was built and tested, and operation was demonstrated with natural gas and propane. The pre-reformer meets all the requirements of the SECA system.

Control and Sensor Development

- A strategy for the control subsystem has been selected and tailored to meet the required system performance and operation characteristics. A multi-level design, including top-level supervisory algorithms and active controls, was developed and implemented in software to manage the various control system tasks.

Thermal Management

- Detailed design of the system heat exchangers was initiated.
- Two concepts for the system tail-gas burner were evaluated. Both were found to be viable solutions and the prototype solution was downselected.

Power Electronics

- System power electronics were fabricated and tested. The power electronics achieved efficiency >94% over a wide range of power (3-6 kW).

Prototype Assembly

- A preliminary prototype system design has been completed, including flow sheet, heat and material balance, package drawing, and bill of materials.
- System schematic was developed and configuration management controlled.
- Bill of materials was also developed and controlled in parallel to the system schematic.

Future Directions

- Kilowatt-class stacks will be built and operated to demonstrate required performance.
- Evaluation and development of all system components will be completed.
- The test plan for the prototype system will be finalized.
- Integrated operation of stack with fuel reformer will be demonstrated.
- Prototype component and subsystem testing will be completed.

- Prototype system will be assembled.
- Final audited cost estimate will be completed and submitted.
- Prototype testing will be conducted at GE according to the test plan.

Introduction

This project focuses on developing a low-cost, high-performance solid oxide fuel cell (SOFC) system suitable for a broad spectrum of power generation applications. The overall objective of the project is to demonstrate a fuel-flexible, modular 3-to-10-kW system that can be configured to create highly efficient, cost-competitive, and reliable power plants tailored to specific markets. The key features of the SOFC system include a fuel-flexible pre-reformer; a low-cost, high-power-density SOFC stack; integrated thermal management; and suitable control and power management subsystems. When fully developed, the system is expected to meet the projected cost of $400/kW.

Approach

The SOFC system is a stationary power module (3 to 10 kW) capable of operating on different fuels. The system consists of all the required components for a self-contained unit, including fuel cell stack, fuel processing subsystem, fuel and oxidant delivery subsystem, thermal management subsystem, and various control and regulating devices.

- The SOFC is a compact arrangement of anode-supported cells (fabricated by the GE tape-calendering process) and metallic interconnects. The stack design is based on an advanced concept that maximizes cell active area and minimizes sealing. The fuel cell can operate directly on light hydrocarbon fuels and incorporates materials for high performance at reduced temperatures (<800°C). These characteristics provide a low-cost, fuel-flexible fuel cell suitable for operating under various conditions. The tape calendering process for manufacturing thin-electrolyte, anode-supported cells is a potentially low-cost, mass-customization technique suitable for high-volume production and automation using available commercial equipment.
- The fuel processor is a catalytic reactor that pre-reforms the hydrocarbon fuel before the gas is fed to the SOFC stack.
- The main thermal management components provide means to utilize the excess heat of the exhaust gases of the SOFC to supply heating to the incoming air and fuel as well as generating steam.
- The control system has a flexible structure that can be modified or optimized for different applications.

The project consists of three phases. Phase I of the project focuses on developing system components having the required operating characteristics, resolving critical technological issues, and demonstrating a prototype system. The Phase I work concentrates on system design and analysis, cost study, stack technology development, fuel processing development, controls and sensors, power electronics, and system prototype assembly and testing. Phase II will demonstrate a packaged system selected for a specified application and further improve technology and assess system cost. Phase III will extend the Phase II effort to field test a packaged system for extended periods to verify the required performance, cost, reliability, and lifetime for commercial uses.

Results

System Design and Analysis: A six-sigma performance analysis for a Phase III target of 40% was performed, including required variabilities from 13 major subsystem parameters. A performance variability analysis of the Phase I conceptual system was performed, including estimated variabilities from 11 major subsystem parameters. Four concepts were compared to the baseline system. The baseline system concept was selected for the conceptual system design. A failure modes and criticality effects analysis for most of the system has been performed. Part-load models for all system

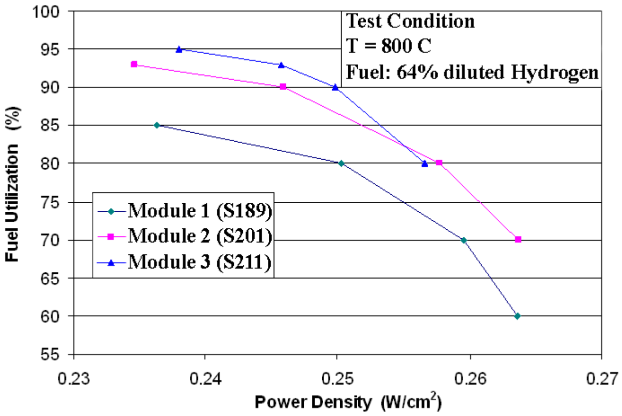

Figure 1. SOFC Module Fuel Utilization

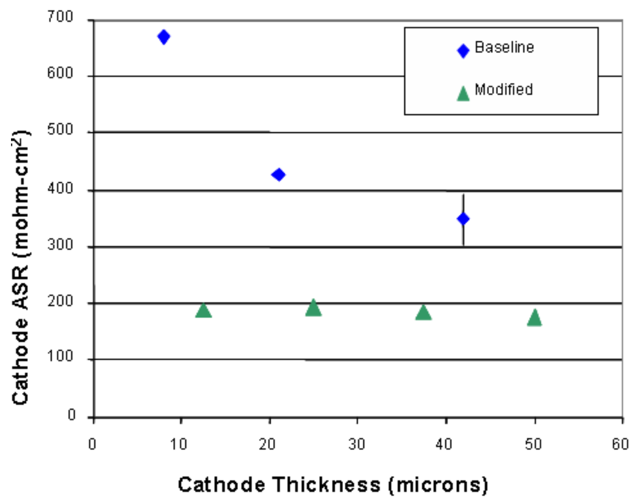

Figure 2. Polarization ASR Measured at Different Thickness for Baseline and Modified Cathodes

components have been developed and incorporated into a system part-load performance model; this will be used to predict the most efficient operational point and the maximum power rated operational point.

Stack Technology Development: A stable fuel utilization of 95% was achieved with 64% hydrogen and balance N_2 at 800°C (Figure 1). At this utilization, a reasonable performance was also achieved: 0.67 V at 0.356 A/cm^2, for a power density of 0.238 W/cm^2. Several single-cell modules and multi-cell stacks of the baseline design were tested. Significant performance improvements have been observed in these tests. For example, under dilute hydrogen at 88% fuel utilization, a power density of 0.193 W/cm^2 was demonstrated at a cell voltage of 0.722 V. While under ATR fuel and the same fuel utilization, the power density was 0.230 W/cm^2 at 0.722 V. At the design current in ATR fuel, the module achieved a power density of 0.276 W/cm^2 at 88% fuel utilization, which approaches the target of 0.300 W/cm^2. Testing of several stacks of the baseline design was performed. One 5-cell, one 6-cell, and two 10-cell stacks were tested with a peak of 75% fuel utilization and maximum power of 0.5 kW. Following the completion of the testing, a risk review was conducted on the stack design. The review identified several major risks, and an improved stack design was then developed. Performance of cathodes has been improved, reducing cathode polarization to ~200 milliohm-cm^2. The cathode polarization area specific resistance (ASR) is plotted in Figure 2 as a function of cathode thickness for both baseline cathode and modified cathode. The modifications produced two benefits: 1) the ASR was reduced by over 50%, and 2) low ASR was maintained at lower cathode thicknesses, which reduces materials and processing cost.

Fuel Processing: Two generations of the ATR external fuel processor design were completed, built, and tested. A photograph of the final ATR processor is shown in Figure 3. The ATR prototype was operated for 42 hours with 9 start/stop cycles. Eight tests were performed using pipeline natural gas, and one was performed using commercial-grade propane. The major operational parameters varied during testing were oxygen-to-carbon ratio, steam-to-carbon ratio, process gas inlet temperature, and reformate mass flow rate. The fuel processor met or exceeded most of the performance targets at the inlet specifications. The reactor demonstrated its ability to reform an alternative fuel (propane) for six continuous hours with no apparent loss of conversion efficiency.

Control and Sensor Development: A multi-level design was developed to manage the various control system tasks. The general control system architecture for this design consists of top-level supervisory algorithms that determine setpoints based on user settings and system conditions. These setpoints are provided to a set of active controls that handle setpoint tracking and disturbance rejection. The baseline control strategy developed in simulation

Figure 3. ATR Fuel Processor

has been updated to facilitate software development and testing. The requirements for the control software are that it execute in real-time and is robust. The target update rate for the control software is currently 0.01 seconds. Preliminary testing with all of the input A/D data, BIT check, supervisory controls, active controls, and output D/A shows that the software can execute in the range of 0.0002 to 0.0003 seconds. Therefore, significant margin exists for execution of the software in the real-time environment. The robustness of the real-time control software was verified by extended continuous operation (>40 hours), and several failure mode investigations were performed such as loss of controller or host PC power.

<u>Thermal Management</u>: The primary components of the thermal management subsystem include a combustor, cathode air preheater, steam generator, and fuel processor reactant preheaters. Combustor development activities have focused on determining system design considerations necessary to operate either a catalytic-type burner or a more conventional, diffusion-type burner. The analysis completed to date shows that both combustor options represent viable approaches to tail-gas combustion. A catalytic approach was chosen for the prototype system to allow increased design flexibility. Activities related to the cathode air preheater were focused on two areas: 1) the procurement of a heat exchanger and 2) determination of heat exchanger sizing methodology to accommodate off-design operation.

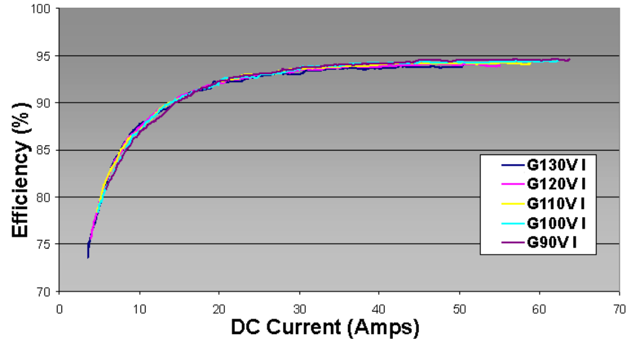

Figure 4. Inverter Efficiency Curve

<u>Power Electronics</u>: Efficiency testing was conducted on two prototype inverters at GE. This data was necessary for down-selecting an inverter that will be used in the prototype system. Overall inverter efficiency is calculated as the total AC power output of the unit divided by the total DC power input. Efficiency curves were generated for multiple DC input voltages. The efficiency for the selected inverter is generally above 94% for DC power greater than 3 kW (Figure 4). The measurement uncertainty for the efficiency is calculated to be approximately ±0.25%, but the results have been consistent throughout the testing of the inverter.

<u>Prototype System Assembly</u>: The prototype system will be assembled based on the concept design developed in this project. The prototype system design will at conclusion include process and instrumentation diagrams; system heat and material balances at rated conditions and off-design points; defined startup and shutdown procedures; failure mode and effects analysis; specified, designed, and identified components; designed control system; and designed thermal management system. The initial prototype system schematic was devised. The schematic created a baseline for prototype system analysis activity and the bill of materials (BOM). The BOM lists each component shown on the schematic, quantities, technical parameters to be used

for hardware identification, and the owner responsible for that component. Layout concepts for the prototype system have been developed utilizing actual component design drawings for those items that have been identified to date and derived conceptual design models for unidentified components.

Conclusions

- A conceptual design of the SECA system for stationary (residential) applications has been developed.
- SOFC modules and stacks of the baseline design have been built and operated and show significant performance improvements. Extraordinarily high fuel utilizations up to 95% in 64% H_2-36% N_2 at 800°C have been demonstrated.
- An ATR pre-reformer for the SECA system has been designed, built and tested on two types of fuels and meets the system requirements.
- A multi-level design for the control subsystem, including top-level supervisory algorithms and active controls, has been developed and implemented in software for the SECA system.
- Efficiencies of >94% for inverters have been demonstrated to meet the SECA system requirement.
- A preliminary design for the prototype system has been developed. Schematic and BOM for the system have been established.

FY 2004 Publications/Presentations

1. N. Q. Minh, "Development of Solid Oxide Fuel Cell Systems for Power Generation Applications", 2003 Fuel Cell Seminar Abstracts, Courtesy Associates, Washington, DC, 2003, p. 892.

2. A. B. Campbell, J. F. Ferrall, N. Q. Minh, "Solid Oxide Fuel Cell Power System", VF-007232, 29th Annual Conference of the IEEE Industrial Electronics Society, Roanoke, VA, November 2-6, 2003.

3. N. Q. Minh, "SECA Solid Oxide Fuel Cell Program", presented at the SECA Annual Workshop and Core Technology Program Peer Review in Boston, MA, May 11-13, 2004.